Limnologica 40 (2010) 126–133

Contents lists available at ScienceDirect

Limnologica

journal homepage: www.elsevier.de/limno

Effects of sampling effort on the estimation of spatial gradients in a tropical reservoir impacted by an oil refinery

Ricardo M. Pinto-Coelho*, Ludmila S. Brighenti, José F. Bezerra-Neto, Cid Antônio Morais Jr., Alan Vieira Gonzaga

Laboratório de Gestão de Reservatórios Tropicais, Setor de Ecologia, Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais, CP 486, 31270-901 Belo Horizonte, Minas Gerais, Brazil

ARTICLE INFO

Article history:
Received 7 October 2009
Accepted 27 November 2009

Dedicated to Prof. Dr. Walter Geller on the occasion of his 65th birthday anniversary

Keywords:
Oil refinery
Tropical reservoir
Spatial gradients

ABSTRACT

We investigated the effects of increase in sampling effort (30–1043 sampling points) on the accuracy of assessment of the spatial patterns of surface-water quality in a eutrophic tropical reservoir. The investigation was carried out during the dry season, when previous investigations showed that the spatial heterogeneity is more stable. A multi-parameter Yellow Springs Instruments probe coupled to a TechGeo D-GPS was used. This system is equipped to measure and store in a continuous recording mode, several physical and chemical parameters linked to geographical coordinates obtained with a precision of less than 1 m. We used different geostatistical approaches to determine the optimal number of sampling points required to reflect the real spatial patterns of water quality in the system. This approach was tested in a small tropical reservoir (Ibirité) that receives effluents from an oil refinery (the state-owned REGAP oil refinery, PETROBRAS) located near the city of Belo Horizonte. The study showed not only that the spatial patterns of water quality are significantly affected by sampling effort but also it was demonstrated that the establishment of an adequate sampling program is a critical point for the precise identification of source points of pollution. The results of this investigation enabled us to demonstrate the potential uses and limits of this method for rapid assessment of the water quality of lakes and reservoirs that receive external inputs of water contaminants or nutrients.

Introduction

According to the Brazilian Electricity Regulatory Agency (ANEEL, 2009), Brazil has 67 large hydroelectric plants (> 100 MW). The number of medium and small reservoirs is not precisely known, but is probably much higher. The most important rivers in southeastern and southern Brazil, such as the Rio Grande, Tietê, Paranapanema, Iguaçú, Paraná, and Rio Uruguai are gradually being transformed into chains of reservoirs. Other large rivers such as the São Francisco and Tocantins also have important hydroelectric plants. In the near future, large man-made lakes will appear along other Amazon rivers such as the Xingú and Madeira. Like their counterparts in the temperate zone, tropical reservoirs are also suffering from an array of environmental problems. However, because of the climate (i.e., higher mean temperatures, more intense and seasonal rainfall in the catchment basin), tropical systems show much wider temporal and spatial variations (Pinto-Coelho, 1987).

Environmental problems such as eutrophication, loss of species richness, spreading of new (exotic) species, greenhouse gas emissions (i.e. CH_4), spreading of waterborne tropical diseases, silting, and water pollution and contamination are commonplace in these tropical man-made lakes. Thus, providing appropriate advice to local authorities regarding the maintenance of good water quality represents an enormous challenge for limnologists.

Improving knowledge about the morphometric features of man-made reservoirs is clearly a priority for Brazilian limnology. At the beginning (up to 1990), much of the limnological effort on these tropical and subtropical reservoirs consisted of studies based on a temporal (seasonal) series of samples concentrated at a single point, usually located in the deepest region of the reservoir, near the dam (e.g., Tundisi et al., 1988). This sampling strategy was based on the assumption that this central point would summarize the behavior of the entire lake. A second phase of limnological studies in Brazilian reservoirs is represented by investigations focused on the spatial heterogeneity of these systems. Usually, a typical study of this category was based on a series of sampling points ($n \leq 30$) scattered in the three main regions of the reservoirs: riverine, transition, and lacustrine (e.g., Andrade et al., 1988; Train et al., 2005). The selection of areas and frequency of sampling was done without any consideration of

* Corresponding author. Tel.: +55 31 34092574; fax: +55 31 34092605.
E-mail address: rmpc@icb.ufmg.br (R.M. Pinto-Coelho).

0075-9511/$ - see front matter © 2009 Elsevier GmbH. All rights reserved.
doi:10.1016/j.limno.2009.11.011

quantitative criteria for point selection or sampling effort. Barbosa et al. (1995), reviewing the state of the art of phytoplankton studies in Brazilian freshwaters, pointed out the urgent need for more studies focusing on horizontal patchiness as well as on short-term variations of the plankton community.

These two kinds of limnological approaches have dominated much of the effort in basic research on Brazilian reservoirs for the last three decades. Considering that most Brazilian reservoirs are still suffering from an increasing array of environmental problems, it is reasonable to conclude that this kind of approach has largely failed, not only to describe the functioning of the systems, but also has been unable to serve as a basis for the development of real sustainable uses of these man-made lakes. The detection and adequate measurement of the chemical and biological spatial patterns in man-made lakes is not trivial, since these systems have a quite different limnological behavior if compared to lakes. Reservoirs usually suffer regular fluctuations in water level; they have short residence times and are located in larger watersheds. Thus, these systems are typically dominated by a highly spatial-temporal dynamics (Straškraba, 2005). Moreover, tropical lakes and reservoirs are typically dominated by intense ecological interactions, especially by the close links between fish and phytoplankton communities (Nielssen, 1984). All these different factors may contribute to increase the difficulty of a precise identification of diffuse as well as point sources of pollution in tropical reservoirs.

The detection of spatial patterns is a fundamental step in order to find the real causes of the decay of ecological health of tropical man-made lakes. However, the establishment of an efficient recovery plan of water-quality recovery of these systems is still a distant dream for most Brazilian reservoirs. Perhaps a good start would be to consider the power of morphometry or hydrodynamics to explain the spatial heterogeneity found in some cases. Good knowledge of morphometric features is an essential step to design more-efficient monitoring programs in such highly impacted systems. Thus, the present investigation had the main objective to develop a precise protocol aiming to answer the question: how many sampling points are necessary to describe the spatial (longitudinal) heterogeneity of water quality in a small tropical reservoir suffering from an array of environmental problems? In order to fulfil this task, it was also necessary to carry out a detailed study aiming to provide the first high-precision bathymetric chart of the studied reservoir.

The availability of a detailed morphometry measured with sub-metric precision of a given reservoir opens a series of possibilities of developing applied limnological studies (Resck et al., 2007; Bezerra-Neto and Pinto-Coelho, 2008). One of these possibilities is the approach used by some authors of studying spatial patterns in a reservoir by means of intensive sampling (e.g., Ladson et al., 2006; Kennedy et al., 2008). In the present study, an over-sampling procedure was used, in order to determine the ideal sampling effort that would be necessary to determine the horizontal compartments in a reservoir with great accuracy. From a dense data set of point values, we selected subsets of different sizes in order to evaluate how means and spatial fields based on these subsets differed from each other and from those based on the full data set. Specifically, we evaluated geostatistically (by spatial models) interpolated surfaces of three different attributes that are commonly used in monitoring programs (electrical conductivity, dissolved oxygen, and pH) as a function of sampling density. The spatial models developed were tested by applying the "leave-one-out cross-validation" procedure.

Study area

Most of the hydrographic basin of the Ibirité Reservoir extends over two municipalities, Ibirité (148,535 inhabitants) and Sarzedo (23,282 inhabitants) (Fig. 1). The landscape of the reservoir basin is dominated by large tracts of *Eucalyptus* plantations, a large condominium, small farms, and several industrial plants. These two small cities are part of the metropolitan region of Belo Horizonte, the capital of the state of Minas Gerais. This is the second most important state in the Brazilian federation, considering the number of inhabitants and the degree of economic development (IBGE, 2009).

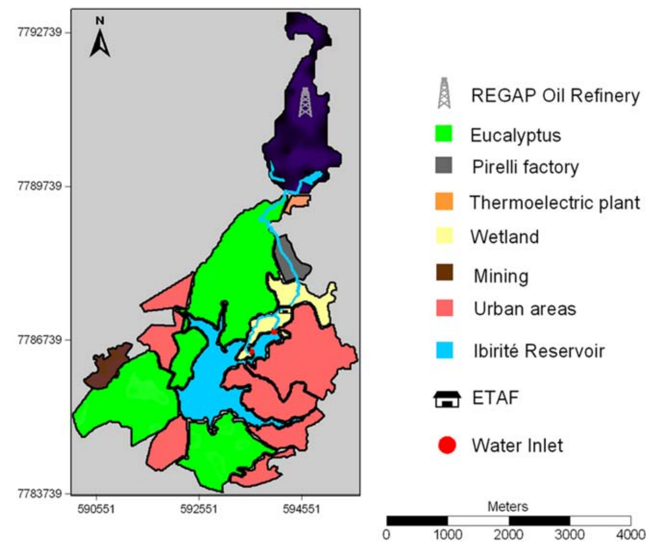

Fig. 1. Major human uses of the Ibirité Reservoir basin, the study area. ETAF is an old wastewater treatment plant that was closed due to operation problems. The state water company (COPASA) provided no information about the reasons that led to the closure of this facility.

The largest industrial plant located in the Ibirité Reservoir hydrographic basin is the oil refinery "Gabriel Passos" or REGAP, which belongs to the Brazilian Oil Company, PETROBRAS (Calmon, 2001). This is a large industrial facility with a processing capacity of 24,000 $m^3\,day^{-1}$ or 150,000 bbl day^{-1} of crude oil and $1.7 \times 10^6\,m^{-3}\,day^{-1}$ of natural gas, both of them coming from the offshore platforms located in the Campos Basin oil fields in the Atlantic Ocean, not far from Rio de Janeiro. For processing this oil, the REGAP plant requires about 10,000 $m^{-3}\,day^{-1}$ of good-quality freshwater, and this water is pumped from the Ibirité Reservoir. After it is used in the plant, the water is treated to remove excess organic matter as well as other contaminants. Basically, this process occurs in two stages. The first stage involves the digestion of organic matter in a series of aerobic digestion tanks. The second stage consists of the deposition of the partially treated water in a small reservoir for some time (Fig. 1). This small pond has prevailing anaerobic conditions. After this two-stage treatment, the water is returned to a small, shallow, hypertrophic arm of the Ibirité Reservoir (Fig. 1).

Material and methods

This investigation was carried in late October, at the end of the dry season (April through October). Previous studies have demonstrated that during this time of year the spatial gradients are usually well established along the reservoir's main axes (Pinto-Coelho et al., 1998).

The bathymetric and physical and chemical data sets were collected simultaneously. An Ohmex® sonar was used to measure the depths. Positional data were acquired with a TECHGEO® differential global positioning system (DGPS). The transducer of the echosounder and the kinematic antenna of the DGPS were set on opposite ends of the same metal tube, in order to reduce errors in positioning due to the inclination of the boat. The sonar transducer was positioned vertically 0.5 m below the water surface.

Survey transects were performed in a zigzag fashion from one side of the lake to the other, with one transect starting where the previous transect ended. A conventional GPS (Garmin 12-channel GPS 76) was also used, to assist with navigation and to help control the boat speed, which was kept under 8 km h^{-1} (Fig. 2).

Precise definition of the shoreline is not only an important element in the process of creating a bathymetric chart, but is also a key factor for obtaining precise thematic charts needed for the geostatistical analyses used in this investigation. The existing cartographic material was not adequate for these purposes. Thus, a new shoreline determination was made.

The calibration of the shoreline of the reservoir was done using the Didger 3.0 software. The polygon containing the shoreline reservoir was taken from a high-precision Google Earth Pro satellite image of Ibirité Reservoir, calibrated by a series of control points taken with the D-GPS using the Didger 3.0 (Golden Software, Inc.). The precision of the calibrated shoreline polygon was within 1.0 m.

The sampling for physical and chemical data was conducted on October 28, 2008 between 09:35 and 11:59 h. The following physical and chemical variables were recorded continuously: pH, dissolved oxygen, and electrical conductivity. These variables were measured using a multi-parameter probe (Yellow Springs Instruments – YSI, model 556), equipped with a data logger. The frequency of data collection was 2.0 s^{-1}. Also, sub-surface samples were taken for determining nutrients (N, P), total suspended solids, and chlorophyll-a at 11 different points covering the central axis as well as all the lateral arms of the reservoir. Total nitrogen (TKN) was measured using the semi-micro-Kjeldahl method (APHA, 1992). Total phosphorus (TP) was obtained using the procedure proposed by Murphy and Riley (1962). Chlorophyll-a was measured using the method proposed by Lorenzen (1967). Finally, total suspended solids (TSS) were measured using the gravimetric procedure (APHA, 1992).

Because the YSI probe does not have a special port to communicate with the DGPS device, a PASCAL computer program was written in order to read information (from text files) delivered by the YSI device and the TechGeo DGPS. This program synchronized the data delivered by the YSI device with the post-processed geographical coordinates delivered by the DGPS, using the time records (GMT) of both devices.

The rate of data acquisition of these variables provided a data matrix with much more information than would be needed to describe the existing spatial variation in the reservoir. These observations allowed us to create a dense grid of points with their corresponding chemical values (DO, pH, and electrical conductivity) (Fig. 2). This is the sampling universe from which different arrays of random data subsets of different sampling sizes were drawn. The objective of this procedure was to compare the statistical differences between the spatial interpolation of an increase in number of sampling points with the full data set. When these differences stabilize at a minimal plateau level, we have the sample size that would retain the main features of the spatial patterns observed for these variables in the reservoir. The leave-one-out cross-validation procedure was used in all cases.

Various interpolation methods were used to generate bathymetric and thematic charts: inverse distance, minimal curvature, nearest neighbor, polynomial regression, Shepard's method, and ordinary and universal Kriging. These procedures were explored to determine the interpolation method that provided the best surface estimation and the best representation of the spatial variability of chemical variables. The Kriging interpolation method was chosen, because the surface that it generates passes through nearly all sampling points, producing the best prediction of the bathymetric as well as the chemical measurements (Georgakarakos and Kitsiou, 2008). The ESRI ArcGIS® Geostatistical Analyst Software (GAS), which provides an extensive set of

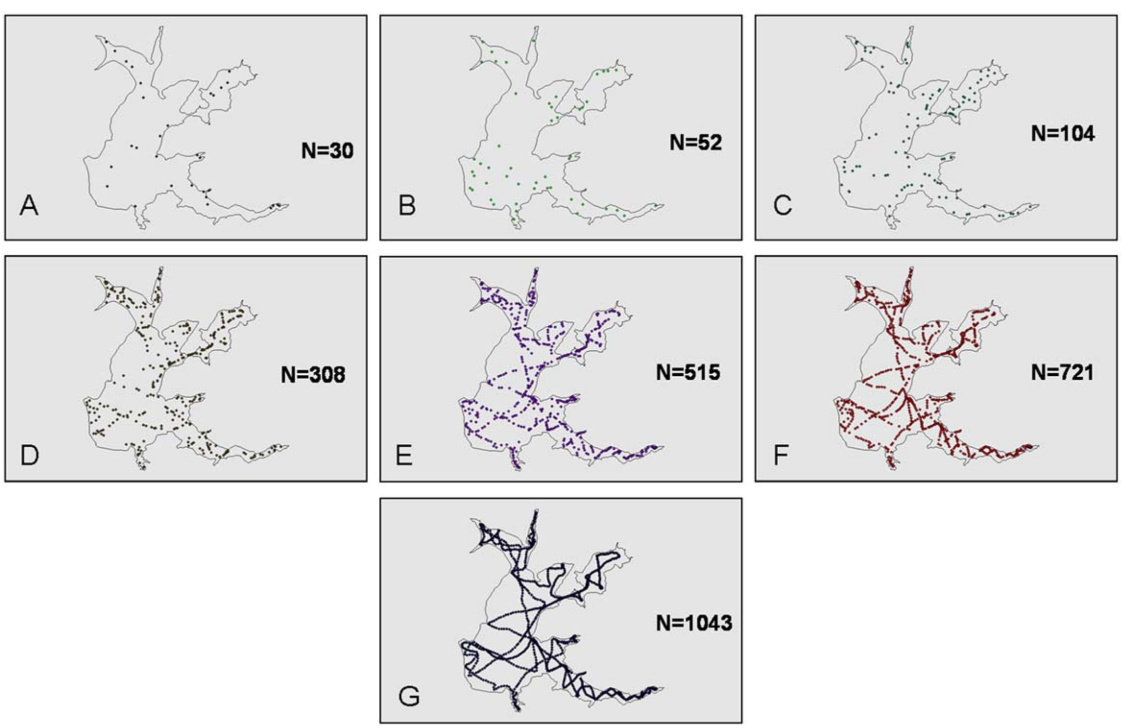

Fig. 2. Spatial representations of some of the data sets originated by the sub-sampling procedure, and the full data set. (A) 30 points, (B) 52 points, (C) 104 points, (D) 308 points, (E) 515 points (F) 721 points, and (G) full data set (1043 points). Only the full data set was used for the bathymetric studies.

tools for performing different Kriging and Co-Kriging methods, was used.

The analysis of empirical variograms and cross-variograms typically aims to generating an empirical variogram and then fitting a parametric model that adequately captures the structure of the empirical variogram. Data are partitioned according to the distance between different pairs of observation locations, so that the bins are as small as possible to retain spatial resolution, and yet large enough that the empirical variogram estimate is stable (Cressie, 1993). The variogram (γ) is estimated as follows (Anttila et al., 2008):

$$\gamma(h) = \frac{1}{2}\sum_{i=1}^{N}[Z(X_i) - Z(X_i + h)]^2$$

where X_i and X_i+h are two points at a certain distance, which belongs to a bin width class of lag h, over all directions or specific to a given direction within the area studied. $Z(X_i)$ and $Z(X_i+h)$ are the values of the physical and chemical variables (conductivity, DO, or pH) at the two locations, and N is the number of data pairs in each lag class. The greater the number of data points, the greater the statistical reliability in each bin width class. The three key parameters in the variogram are the parameters "nugget," "range," and "sill". Usually, these statistics are estimated by applying the spherical model (Cressie, 1993).

According to Rossi et al. (1992), the "nugget" parameter represents the variation at very short distances. This value means the point at which the variogram model appears to intercept the y-axis. The "range" parameter represents the maximum spatial distance, where data are effectively spatially correlated or autocorrelated. The "sill" parameter refers to the maximum variance of the variogram minus the nugget effect. Sometimes the maximum variance, including the nugget, is referred to as the total sill. Correspondingly, a cross-variogram model describes the co-variation (or correlation relationship) between each pair of variables (Journel and Huijbregts, 1978; Cressie, 1993; Goovaerts, 1997). The crossvariogram ($\gamma_{1.2}$) for two variables Z_1 and Z_2 is estimated by the formula:

$$\gamma_{1.2}(h) = \frac{1}{2N}\sum_{i=1}^{N}\{[Z_1(x) - Z_1(x+h)][Z_2(x) - Z_2(x+h)]\}$$

Ordinary Kriging and universal Kriging, which were used in the present study, are gradual and local, and may not be exact, perfectly reproducing the measured data. Kriging selects weights so that the estimates are unbiased and the estimation variance is minimized. Identifying the best variogram may involve running and evaluating a large number of models, a procedure supported by the ArcGIS® Geostatistical software.

Let Z represent the measured value given by the YSI probe the x, y coordinate system, for which distances are linear. Ordinary Kriging provides a statistical model for the process $Z(x, y)$, at all points in space, (x, y), as follows:

$$Z(x, y) = u + e(x, y)$$

where u and $e(x, y)$ are the overall, large-scale mean of the process across the spatial domain and the small-scale random fluctuation of the process accordingly. Unlike universal Kriging, ordinary Kriging places very little emphasis on the first mean component, focusing instead on modeling the structure of the small-scale random fluctuation component. Universal Kriging is an extension of ordinary Kriging accommodating a spatially varying trend. It can be used both to produce local estimates in the presence of a trend and to estimate the underlying trend itself. Incorporating the spatially varying trend, the previous equation is modified as:

$$Z(x, y) = u(x, y) + e(x, y)$$

where the mean term is described by the model $u\ (x, y)$.

Finally, the developed models are evaluated by analyzing the leave-one-out cross-validation residuals, and their statistics are compared and tested concerning modeling assumptions and whether standard errors estimated by the model are accurate (Isaaks and Srivastava, 1989).

The leave-one-out cross-validation residuals are generated using the following procedures: (a) create an empirical variogram using all of the N available observations, (b) estimate the theoretical variogram from the empirical variogram, (c) remove the observation from the data set, (d) predict the Kriged value $Z(s_i)$ for the location of the removed observation using the remaining $(N-1)$ observations, (e) calculate the difference between the predicted value and the true value, (f) divide this difference by the Kriging Standard Error (Bradley and Haslett, 1992), and then (g) record the value Sr_i as the standardized residual at the location of the removed observation.

$$Sr_i = \frac{Z(s_i) - \hat{Z}(s_i)}{\mathrm{KSE}}$$

Once the residual at each location has been calculated as described, their distribution is tested for normality, assessing whether the Kriging model assumptions were correct, and if other modeling techniques should be considered.

The different models were compared based on the calculation of the root-mean-squared prediction error (RMS), the average standard error (ASE), and the coefficient of determination (R^2). If the average standard error is close to the root-mean-squared prediction error, the variability in prediction is correctly assessed. If the average standard error is greater than the root-mean-squared prediction error, the variability of the predictions is overestimated; on the other hand, if the average standard error is less than the root-mean-squared prediction error, it is underestimated.

Results and discussion

The error of the shoreline calibration was less than 0.01 m. The bathymetric survey was conducted on 27 and 28 October, 2008. The survey provided 25,612 georeferenced depth measurements. The surface level was measured on both days with a calibrated altimeter, and it remained constant; the reservoir surface remained at an altitude of 798.8 m a.s.l. during both days.

The bathymetric data were processed using the software Surfer 8.0 (Golden Software Co). The reservoir has a total surface area of 2.05 km^2. The total volume is 11.6×10^6 m^3. The mean and maximum depths are 5.65 and 17.67 m, respectively (Table 1). The bathymetric chart (Fig. 3) revealed that the central axis is deeper, with depths over 10 m. All three major reservoir lateral arms are very shallow, with depths less than 6.0 m. One of the reservoir's lateral arms is particularly shallow, with depths usually less than 1.0 m. Precisely in this very shallow arm, there

Table 1
Primary and secondary morphometric parameters of Ibirité Reservoir, Ibitité/Sarzedo/Betim, state of Minas Gerais.

Parameter	Value
Surface area (A)	2.05 km^2
Volume (V)	11.6×10^6 m^3
Shoreline length (P)	14.014 m
Effective maximum length (L_e)	2.506 m
Effective maximum width (W_e)	1.208 m
Maximum depth (Z_{max})	17.67 m
Volume development (D_v)	0.96
Shoreline development (D_l)	2.74
Mean slope (α)	2.18%

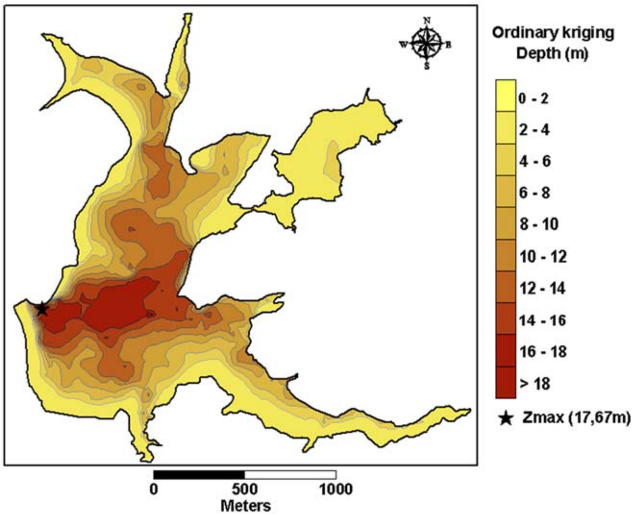

Fig. 3. Bathymetric chart of Ibirité Reservoir, indicating the deepest point in the lake (star).

Table 2
Basic statistics of physical and chemical properties of Ibirité Reservoir.

	Temperature (*T*) (°C)	Electrical conductivity (Cond) ($\mu S\ cm^{-1}$)	Dissolved oxygen (DO) ($mg\ O_2\ L^{-1}$)	pH
Minimum	25.6	336	3.9	8.8
Maximum	34.2	496	7.0	12.0
Mean	27.7	419	6.0	10.9
SD (*N*=1043)	2.0	33	0.7	0.6

Water temperature, electrical conductivity, and dissolved oxygen. Sampling date: 27 October, 2008.

are two important pollution points, the two outfalls of partially treated wastewater from the REGAP oil refinery (Fig. 1). As will be seen later, this is a critical factor affecting the water quality of the reservoir.

The morphometric features of Ibirité Reservoir contribute to increase in eutrophication in this ecosystem. If we consider: (a) that the REGAP refinery processes a daily volume of $10^4\ m^3$ of freshwater and most of this water flowing into the reservoir carries a series of contaminants, and (b) that the reservoir has a total volume of $10^7\ m^3$, it is easy to conclude that these two pollution points represent an annual contribution of almost 4% of the total reservoir volume. Considering that the refinery has been operating for more than 30 years, this means that the operation of this facility has led to an enormous impact on the reservoir's water quality.

The YSI probe collected 2087 single point measurements. The data set confirmed the ecological condition of hypertrophy, with high conductivity readings, wide oscillations in surface dissolved oxygen levels, and high pH. The surface temperatures ranged from 25.6 to 34.2 °C, with a mean value of 27.7 °C. Conductivity was very high, with values ranging from 336 to 496 $\mu S\ cm^{-1}$ and a mean of 419 $\mu S\ cm^{-1}$. Dissolved oxygen also showed conspicuous oscillations, varying between 3.9 and 7.0 $mg\ O_2\ L^{-1}$ with a mean of 6.0 $mg\ O_2\ L^{-1}$. The pH remained above 8.0 (8.8–12.0), with a mean of 10.9 (Table 2).

We also collected sub-surface (0.5 m depth) water samples for analyses of total solids, nutrients, and chlorophyll-a (Table 3). The lake water is rich in nitrogen and phosphorus, with mean values of 6.2 $mg\ L^{-1}$ TKN and 394 $\mu g\ L^{-1}$ TP, respectively. The reservoir was undergoing a bloom of phytoplankton during the day of sampling. As expected, the concentrations of chlorophyll-a were very high throughout the reservoir (mean 122 $\mu g\ L^{-1}$). Total solids (TSS) oscillated between 37.5 and 700.0 $mg\ L^{-1}$. These results confirmed the hypertrophic state of Ibirité Reservoir.

Table 3
Total nitrogen (TKN), total phosphorus (TP), chlorophyll-a, and total suspended solids (TSS).

	Total nitrogen (TKN) ($mg\ L^{-1}$)	Total phosphorus (TP) ($\mu g\ L^{-1}$)	Chlorophyll-a (Chl-a) ($\mu g\ L^{-1}$)	Total suspended solids (TSS) ($mg\ L^{-1}$)
Minimum	1.3	114	216	37.5
Maximum	13.8	979	11	700.0
Mean	6.2	394	1293	122.2
SD (*N*=11)	4.4	292	361	195.7

Sampling date: 27 October, 2008.

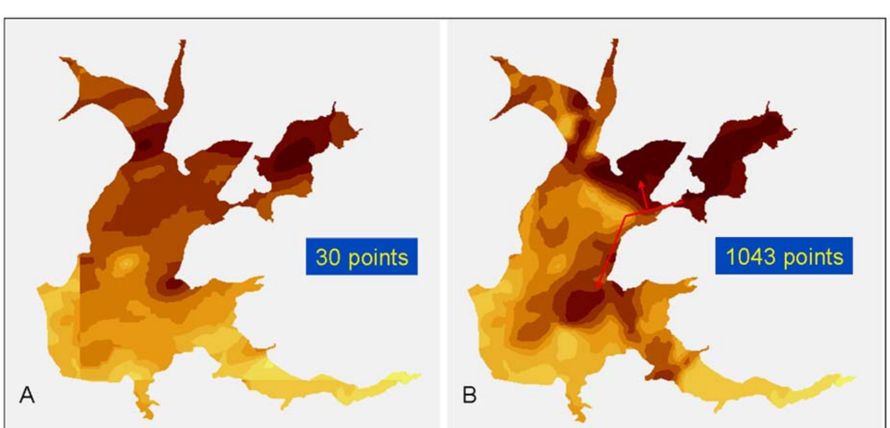

Fig. 4. Thematic charts of sub-surface electrical conductivity with different levels of sub-sampling: (A) ordinary Kriging using only 30 randomly selected points (left); (B) ordinary Kriging using the full data set.

The relationship between human activities in the hydrographic basin and the spatial and temporal patterns of water quality of reservoirs is crucial, not only to understand the system functioning, but also to establish a recovery plan when this is needed. Much of the limnological effort in Brazilian reservoirs has so far been concentrated on the internal dynamics of these systems. Very few investigations have focused on the impacts of human activities such as agriculture, cattle ranching, or industrial concentration (e.g., Pinto-Coelho et al., 2005).

A previous study demonstrated the advanced eutrophication status of Ibirité Reservoir and the possible role of REGAP in contributing to this situation (Pinto-Coelho et al., 1998). However, this relationship was not clearly established because of the lack of a more precise description of the reservoir's spatial patterns of water quality. The present investigation demonstrated that the highest values of surface conductivity in this lake are associated with the inlet of REGAP effluents. Furthermore, if we simultaneously analyze the bathymetric and conductivity charts (Figs. 3 and 4), it is possible to trace back the possible routes of dissemination (arrows) of the polluted water coming from REGAP into other compartments of the lake. The spatial patterns of conductivity obtained with 30 sampling points did not clearly show the association between the conductivity picks inside the REGAP arm and the other areas of the reservoir with higher values for this variable. Nevertheless, this relationship was clear with a denser array of sampling points (see arrows in Fig. 4). It is important to keep in mind that environmental officials of PETROBRAS have traditionally denied this clear association between the REGAP activities and the bad water quality of the reservoir.

An oil refinery usually requires large amounts of freshwater to process crude oil. The freshwater requirements of such plants vary from 0.4 to 1.6 times the total volume of oil processed in the plant (Santaella et al., 2009). For transforming crude oil into gasoline, diesel, aviation kerosene, or naphtha, a long list of different chemicals and solvents are used (Alva-Argáez et al., 2007). Thus, the effluents of these plants are usually heavily contaminated with several types of organic and inorganic pollutants such as phenols, sulphides, ammonium, cyanides, polyaromatic and aliphatic hydrocarbons, and different inorganic salts (Santaella et al., 2009). Most oil refineries have treatment plants, but even after treatment the final effluent contains many contaminants. The concentrations of these substances are usually below the critical values to produce lethal effects on the existing biota. However, continuous input of these compounds may cause serious ecological problems in the long term. Increase in threshold levels in water conductivity may be one of these effects.

The higher levels found for electrical conductivity in the Ibirité Reservoir contrast markedly with the average values for this variable in most of the reservoirs in this region. Serra Azul and Vargem das Flores are two reservoirs located not very far from Ibirité (less than 25 km in both cases). Both of them are used by the state-owned COPASA Company for public water supply. Conductivity in the Serra Azul Reservoir seldom exceeds 30 μS cm^{-1} (Pinto-Coelho et al., in preparation). This is an oligotrophic reservoir and is an important source of good-quality water for Belo Horizonte. Vargem das Flores is a mesotrophic reservoir that is moderately impacted by human activities, including the diversion of untreated wastewater into some of its tributaries. These impacts are causing distinct spatial gradients in the water quality. Despite all these impacts, the conductivity is always below 100 μS cm^{-1} in Vargem das Flores (Freire and Pinto-Coelho, 1986).

In this study, the spatial patterns obtained for conductivity, pH, and dissolved oxygen were carefully evaluated for their accuracy. The PASCAL routine synchronized the YSI data with the TechGeo D-GPS post-processed geographical coordinates. Since these devices have different ratios of data logging, the final data matrix containing the geographical coordinates and the physical and chemical data provided by the YSI 556 probe contained only 1043 points. The root-mean-square (RMS) statistics can be used for estimating the geostatistical model. The lower the RMS value, the better is the quality of the model. If the RMS is close to zero, the variability in prediction is correctly assessed. The RMS values for different data subsets and the full data sets are represented in Fig. 5. Each point represents the average value of RMS ($\pm$ standard error) of ten different interpolations using 30, 52, 104, 308, 515, 721, and 1043 points (the full data set). A similar pattern of decrease in RMS values was found for all three variables

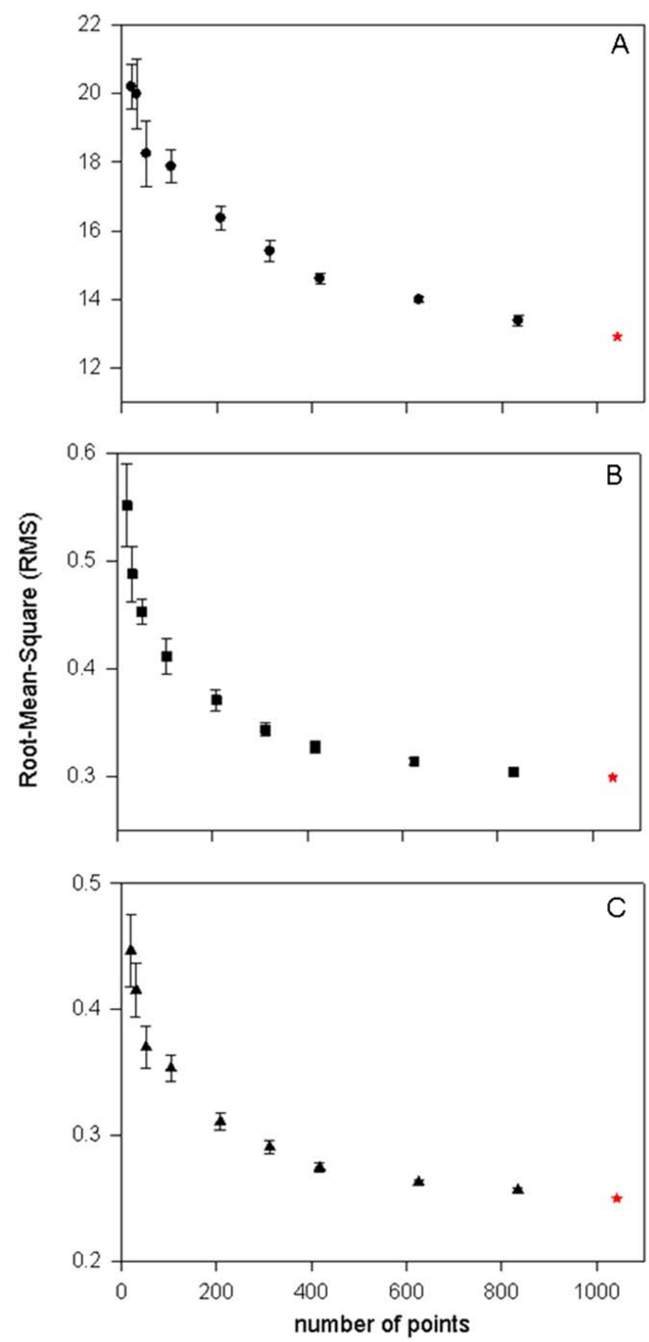

Fig. 5. Root-mean-square values of increasingly large subsets of data for the three variables used in this analysis: (A) electrical conductivity (top), (B) dissolved oxygen (middle), and (C) pH (bottom).

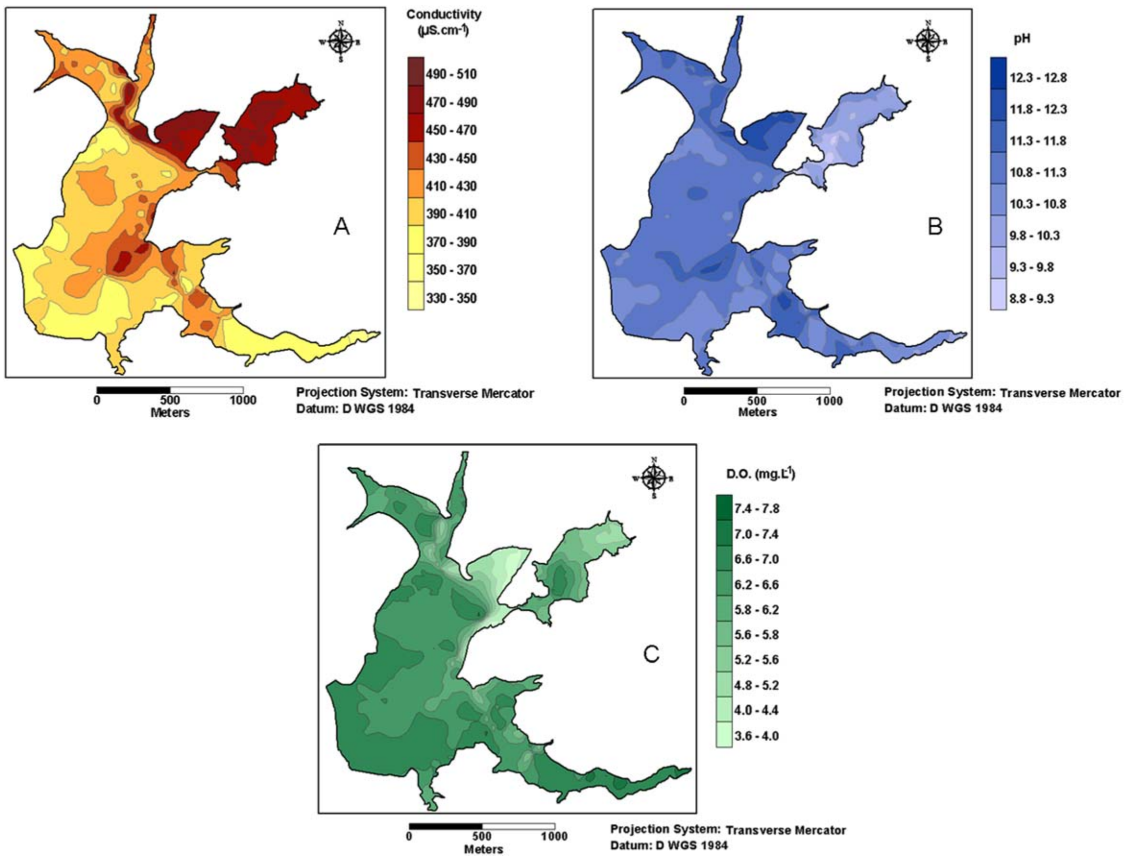

Fig. 6. Thematic charts for the three variables used in the study of sample density: electrical conductivity (A), pH (B), and dissolved oxygen (C).

(Fig. 5). Below 100 points, the RMS values usually were much higher, possibly reflecting the loss of much of the original spatial information.

In all cases, there was only a slight decrease in RMS values for interpolations using more than 400 points. The RMS values were clearly higher for electrical conductivity. The average RMS values for this variable decreased from 20.9 (20 points) to 12.91 (1043 points). The lowest RMS values were obtained for pH (Fig. 5). This 400 points plateau reflects the highly heterogeneous nature of this water body. This plateau means that this is the minimum number of sampling points that should be considered for a comprehensive monitoring program to be applied in this reservoir. It is important to stress that the environmental legal basis of the country does not require any previous study to determine the optimal number sampling points to be applied in the monitoring programs affecting hundreds of reservoirs all over the country (Machado, 1998).

As expected, the geostatistical analyses confirmed the existence of spatial patterns in Ibirité Reservoir. There were clear modifications of sub-surface waters in the lake compartment where the wastewater channel from the REGAP oil refinery enters the lake water. All three variables considered (pH, DO, and electrical conductivity) exhibited spatial patterns that reflected the impact of this polluted compartment into the main reservoir axis (Fig. 6).

High daytime pH values ($pH > 8.0$) are very common in hypertrophic tropical waterbodies. This pattern is often associated with supersaturation of surface dissolved oxygen and higher chlorophyll-a concentrations ($> 80\,\mu g\,L^{-1}$ chlorophyll-a). Several hypertrophic Brazilian reservoirs show a similar pattern (Tundisi et al., 1988). During this investigation, the Ibirité Reservoir was undergoing a bloom of phytoplankton, and several floating islands of the macrophyte *Eichhornia crassipes* were observed. These are classical signs of the hypertrophic condition. Furthermore, there are records of mass fish mortality, mostly due to blooms of toxic strains of cyanobacteria (A. Giani, pers. comm.).

This study demonstrated that the accurate description of spatial gradients in reservoirs requires a sampling effort that is considerably higher than the sampling effort traditionally used in most published work on spatial gradients, at least in Brazilian reservoirs. The sampling effort of such studies was usually below 30 sampling points, regardless of the complexity of human activities in the basin or the lake morphometry. The analysis of spatial patterns is greatly improved if an accurate map of the morphometry and bathymetry of the reservoir is available. Furthermore, the study also showed that the use of a multiparameter probe coupled to a D-GPS is a low-cost method that can rapidly describe the spatial patterns of a given reservoir. Finally, this kind of approach can be used to improve the existing monitoring programs, since it was able to detect the immediate cause of pollution in the system.

Acknowledgements

The authors wish to thank the distance-education program "*Fundamentos em Ecologia e Tópicos em Gestão Ambiental*" (convênio 3443-14 FUNDEP/UFMG) for financial support (fuel, consumable material, and small services). They also thank the research project "*Delimitação de Parques Aquícolas nos Reservatórios de Furnas e Três Marias*" (grant 8713 FUNDEP/SEAP/SECTES) for providing the resources needed to purchase most of the equipment and software used in this study. The FAPEMIG foundation provided the postdoctoral fellowship of Dr. José Fernandes Bezerra Neto.

References

Agência Nacional de Energia Elétrica – ANEEL, 2009. http://www.aneel.gov.br/.
Alva-Argáez, A., Kokossis, A.C., Smith, R., 2007. The design of water-using systems in petroleum refining using a water-pinch decomposition. Chem. Eng. J. 128 (1), 33–36.
APHA, 1992. Standard methods for the examination of water and wastewater, 18th ed. American Public Health Association, Washington, DC.
Andrade, L.F., Brunkow, R.F., Xavier, C.F., Domingues, L.L., 1988. Fitoplâncton e características físico-químicas do reservatório de Itaipu. In: Tundisi, J.G. (Ed.), Limnologia e Manejo de Represas. Academia de Ciências do Estado de São Paulo, FAPESP, São Paulo (SP), pp. 205–268.
Anttila, S., Kairesalo, T., Pellikka, P., 2008. A feasible method to assess inaccuracy caused by patchiness in water quality monitoring. Environ. Monit. Assess. 142, 11–22.
Barbosa, F.A.R., Bicudo, C.M., Huszar, V.L., 1995. Phytoplankton studies in Brazil: community structure, variation and diversity. In: Tundisi, J.G., Bicudo, C.M., Tundisi, T.M. (Eds.), Limnology in Brazil. Brazilian Academy of Sciences, Rio de Janeiro, pp. 19–36.
Bezerra-Neto, J.F., Pinto-Coelho, R.M., 2008. Morphometric study of Lake Dom Helvécio, Parque Estadual do Rio Doce (PERD), Minas Gerais, Brazil. Acta Limnol. Brasiliensia 20 (2), 161–167.
Bradley, R., Haslett, J., 1992. High-interaction diagnostics for geostatistical models of spatially referenced data. The Statistician 41, 371–380.
Calmon, S.V., 2001. A Refinaria Gabriel Passos – REGAP, PETROBRAS. http://www2.petrobras.com.br/ri/port/ApresentacoesEventos/Apresentacoes/pdf/apr_regap_21_11_01.pdf.
Cressie, N.A.C., 1993. In: Statistics for Spatial Data. John Wiley & Sons, New York, NY, USA.
Freire, B.M., Pinto-Coelho, R.M., 1986. Composição e distribuição horizontal do zooplâncton no reservatório de Vargem das Flores, Betim/Contagem, Minas Gerais. Revista Ciência e Cultura (Sociedade Brasileira para o Progresso da Ciência – SBPC) 38 (5), 919–927.
Georgakarakos, S., Kitsiou, D., 2008. Mapping abundance distribution of small pelagic species applying hydroacoustics and Co-kriging techniques. Hydrobiologia 612, 155–169.
Goovaerts, P., 1997. In: Geostatistics for Natural Resources Evaluation. Oxford University Press, New York, USA.
Instituto Brasileiro de Geografia e Estatística – IBGE, 2009. A População Brasileira: Cidades e Estados. http://www.ibge.gov.br/home/.
Isaaks, E.H., Srivastava, R.M., 1989. In: Applied Geostatistics. Oxford University Press, New York, USA.
Journel, A.G., Huijbregts, C.J., 1978. In: Mining Geostatistics. Academic Press, London, UK.
Kennedy, C., Genereux, D.P., Mitasova, H., Corbett, D.R., Leahy, S., 2008. Effect of sampling density and design on estimation of streambed attributes. J. Hydrol. 355, 164–180.
Ladson, A.R., Grayson, R.B., Jawecki, B., White, L.J., 2006. Effect of sampling density on the measurement of stream condition indicators in two lowland Australian streams. River Res. Appl. 22, 853–869.
Lorenzen, C.J., 1967. Determination of chlorophyll and pheo-pigments: spectrophotometric equations. Limnol. Oceanogr. 12, 343–346.
Machado, P.A.L., 1998. In: Direito Ambiental Brasileiro seventh ed. Malheiros Editora, São Paulo (SP), p. 894.
Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.
Nielssen, J.P., 1984. Tropical lakes: functional ecology and future development. The need of a process-orientated approach. Hydrobiologia 113, 231–242.
Pinto-Coelho, R.M., 1987. Flutuaçoes sazonais e de curta duração na comunidade zooplanctônica do Lago Paranoá, Brasília, DF, Brasil. Revta. Brasil. Biol. (Brazil. J. Biol.) 47 (1/2), 17–29.
Pinto-Coelho, R.M., Nunes, C.S., Barbeitos, M., Morais, C.A., Guerra, S.T., 1998. O impacto da refinaria Gabriel Passos na estruturação da comunidade zooplanctônica no reservatório de Ibirité, Betim; Ibirité, Minas Gerais. Rev. Bios (Pontifícia Universidade Católica de Minas Gerais, PUC-MG) 6 (6), 11–19.
Pinto-Coelho, R.M., Azevedo, L.M.A., Rizzi, P.E.V., Bezerra-Neto, J.F., Rolla, M.E., 2005. Origens e efeitos do aporte externo de nutrientes em um reservatório tropical de grande porte: reservatório de São Simão (MG/GO). In: Nogueira, M.G., Henry, R., Jorcin, A. (Eds.), Ecologia de Reservatórios. Rima Editora, São Carlos (SP) ISBN:85-7656-058-5, pp. 127–164.
Resck, R.P., Bezerra-Neto, J.F., Pinto-Coelho, R.M., 2007. Nova batimetria e avaliação de parâmetros morfométricos da Lagoa da Pampulha (Belo Horizonte, Brazil). Rev. Geografias 3, 24–37.
Rossi, R.E., Mula, D.J., Journel, A.G., Franz, E.H., 1992. Geostatistical tools for modelling and interpreting ecological spatial dependence. Ecol. Monogr. 2, 277–314.
Santaella, S.T., Silva, F.C.G., Costa, K.O., Aguiar, R., Arthaud, I.D.B., Leitão, R.C., 2009. Tratamento de efluentes de refinaria de petróleo em reatores com *Aspergillus niger*. Eng. Sanit. Ambiental 14 (1), 139–148.
Straškraba, M., 2005. Reservoirs and other artificial water bodies. In: O' Sullivan, Reynolds, C.S. (Eds.), The lake handbook, vol. 2. Blackwell, Oxford, pp. 300–328.
Train, S., Jati, S., Rodrigues, L.C., Pivato, B.M., 2005. Distribuição espacial e temporal do fitoplâncton em três reservatórios da bacia do rio Paraná. In: Rodrigues, L., Thomaz, S.M., Agostinho, A., Gomes, L.C. (Eds.), Biocenoses em Reservatório. Rima Editora, São Carlos, SP, pp. 73–85.
Tundisi, J.G., Matsumura-Tundisi, T., Henry, R., Rocha, O., Hino, K., 1988. Comparação do estado trófico de 23 reservatórios do estado de São Paulo: eutrofização e manejo. In: Tundisi, J.G. (Ed.), Limnologia e Manejo de Represas. Academia de Ciências do Estado de São Paulo, FAPESP, São Paulo (SP), pp. 165–205.